

### A Low-Power Low-Mass Dual-Polarization Sensitive Submillimeter-Wave Radiometer/Spectrometer.

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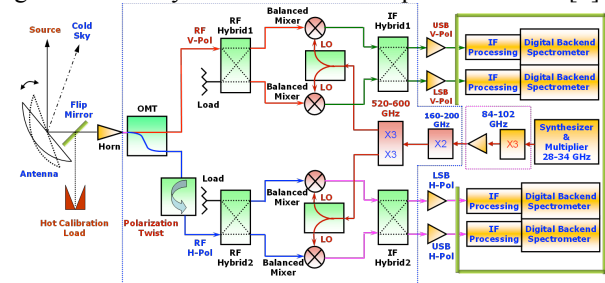
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**Introduction:** Using newly developed CMOS components and silicon micromachining technology that enable low-mass and highly integrated receivers, we are developing a state-of-the-art submillimeter-wavelength radiometer/spectrometer instrument for planetary orbiter missions to Mars, Venus, Titan, and the Galilean moons. Our flexible receiver architecture provides a powerful instrument capability in a light-weight, low-power consuming compact package, which offer unprecedented sensitivity performance, spectral coverage, and scalability to meet the scientific requirements of multiple missions. The instrument will allow a large number of chemical species, such as water, NO<sub>2</sub>, N<sub>2</sub>O, NH<sub>3</sub>, SO<sub>2</sub>, H<sub>2</sub>S, CH<sub>4</sub>, and HCN, among others. It will also be able to pinpoint their location in latitude, longitude, and in altitude.

Space-based terahertz heterodyne radiometry-spectrometry at these frequencies has proven useful for measuring trace constituent abundances and physical properties under all climate conditions, including high dust loading [1]. The terahertz transitions of polar molecules permit detection of numerous trace species at parts per trillion to parts per billion sensitivity. As an emission measurement, observations are carried out continuously in a passive mode without the need for any time-restricted event such as a solar occultation. At these wavelengths, a moderate-sized antenna (30-cm effective) can yield high-spatial resolution measurements ( $\lambda/D \approx 1.8 \times 10^{-3}$  at 550 GHz), while ultrahigh spectral resolution ( $\lambda/\Delta\lambda > 10^6$ ) provides clear line separation and well-defined line profiles. Submillimeter-wave measurements are an ideal complement to infrared measurements of thermal inertia. Moreover, they offer several advantages over the infrared (IR) measurements: (i) much higher spectral resolution ( $>10^6$ ) is possible because of the smaller absolute Doppler line broadening at lower frequencies, (ii) terahertz measurements are not blinded by aerosols or dust because the wavelengths are much longer than dust grain/aerosol size, eliminating scattering, (iii) some constituents (such as nitriles) have much stronger line intensities at submillimeter wavelengths, thus making possible detection at much lower concentrations, and (iv) radiometry allows characterization of surface properties by measuring thermal emission from dielectric surfaces.

**Instrument Design:** Fig. 1 shows the block diagram of the instrument under development. The instrument features a dual-polarized, sideband separating

receiver sensitive to 520-600GHz, backed by a high-speed digital spectrum analyzers. The two-polarizations are received by a dual-polarization horn followed by a orthomode-transducer (OMT), which separates the two polarizations into two separate channels. Each channel is down-converted to 3GHz by a sideband separating Schottky-diode mixers pumped by a diode-based multiplier chain. A CMOS synthesizer is used to generate the fundamental LO signal that is multiplied up to 520-600GHz. The four IF channels (upper and lower sidebands for both polarizations) are amplified using low-power Silicon-Germanium amplifiers. Finally, the signal is digitized and a spectrum is generated by a CMOS spectrometer [2].



**Figure 1:** Schematic block diagram of a 520-600 GHz dual-polarized sideband separating receiver with two sideband outputs in each polarization for radiometry and spectroscopy applications.

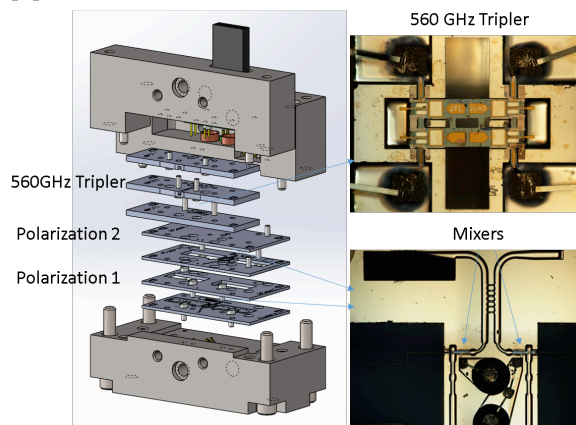
Several innovations have enabled the radical increase in capabilities of submillimeter-wave instruments while reducing the total power consumption of the instrument. Most significantly, the CMOS components have reduced the power of the spectrometer and synthesizer, which previously have consumed tens of watts on previous submillimeter-wave instruments. Compared to a FPGA-based spectrometer, the power has been reduced from 12W to less than 1W per channel. Similarly, the CMOS synthesizer consumes less than 0.5W, saving over 5W compared to a DRO-based synthesizer. Higher submillimeter-wave circuit complexity is enabled by a novel silicon-micromachining process that utilizes microfabrication processes to produce precision waveguide structures. Finally, advances in commercial Gallium Nitride power amplifiers reduce the LO power consumption from 20W to 6W.

**Technological Advances:** Discussion of each of the technological advances that enable this instrument follow.

**CMOS Spectrometer:** Previously, wide-bandwidth digital spectrometer processors were implemented as auto-correlators architectures or chirp-transform spec-

trometers (CTSs). These components have been massive and power hungry. Due to the much higher circuit speeds available from modern sub-micron CMOS technology, it is now possible to construct a much lighter and lower-power consuming system-on-chip (SoC) replacing even FPGA based spectrometers. The chip has integrated 7-bit digitizers, channel offset self-calibration, interleaving functions, clock management system, and vector accumulation. Currently it has a 512 channel quadrature output with integrated USB 2.0 controller. The entire back end including support PCB is 5cm x 8cm x 1cm and consumes only 200mW of total power. A higher speed 10 GS/s SoC chip with 8K channels is also under development [3].

**CMOS Synthesizer:** The CMOS synthesizer uses a conventional (charge-pump / phase detector / freq divider / VCO) phase-locked-loop (PLL) which provides coverage across 43-53 GHz followed by an on-chip frequency doubler to provide the higher 83-100 GHz output. Decreased frequency steps are achieved by clocking the synthesizer with a direct-digital frequency synthesizer (DDFS), enabling frequency steps less than 500MHz at the detection frequency. Also integrated within the same device is an integrated W-band power amplifier, allowing the module to output at least 1 mW of output power across the band. The entire synthesizer module consumes 220 mW with a phase noise of -90 dBc [4].



**Figure 2:** An exploded view of the silicon micromachined assembly. (Left) Seven layers are used to house the tripler and two sideband separating receivers, one for each polarization. (Top Right) The quad-chip 560GHz tripler used to pump the Schottky mixers. (Bottom Right) A sideband-separating receiver that supports two fundamental-balanced Schottky mixers.

**Silicon Micromachining:** Increased submillimeter-wave circuit complexity is achieved by manufacturing the 520-600 GHz, dual-polarization receiver with silicon micromachining. This process uses a combination of photolithographic techniques and Deep Reactive Ion Etching (DRIE) of silicon to form the waveguide-

based circuit. This process provides high precision structures ( $\pm 1\mu\text{m}$ ), allowing for higher-density waveguide circuit integration. Fig. 2 shows an exploded view of the front-end assembly, showing the seven silicon layers that support the two receivers and the 560GHz tripler [5].

**Conclusion:** A compact, low-power and mass, dual-polarization submillimeter-wave radiometer/spectrometer instrument is being developed for future planetary missions to Mars, Venus, Titan, the Galilean moons and other sites around the solar system. In addition to performing remote limb sounding of planetary atmospheres, the dual-polarization capability allows for remote measurement of a surface's dielectric properties. Several technological innovations have enabled this advance in capabilities while reducing the power budget of the system; namely development of custom CMOS SoCs and silicon micromachining.

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**Acknowledgements:** The research described herein was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, under contract with National Aeronautics and Space Administration.